

Quark Asymmetries and Intrinsic Charm in Nucleons¹

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Abstract: We have developed a physical model for the non-perturbative x -shape of parton density functions in the proton, based on Gaussian fluctuations in momenta, and quantum fluctuations of the proton into meson-baryon pairs. The model describes the proton structure function and gives a natural explanation of observed quark asymmetries, such as the difference between the anti-up and anti-down sea quark distributions and between the up and down valence distributions. We find an asymmetry in the momentum distribution of strange and anti-strange quarks in the nucleon, large enough to reduce the NuTeV anomaly to a level which does not give a significant indication of physics beyond the standard model. We also consider charmed fluctuations, and show that they can explain the excess at large x in the EMC F_2^c data.

Keywords: quark asymmetries, parton density distributions, s-sbar asymmetry, NuTeV anomaly, intrinsic charm

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The low-scale parton density functions give a description of the hadron at a non-perturbative level. The conventional approach to these functions is to make parameterizations using some more or less arbitrary functional forms, based on data from deep inelastic scattering and hadron collision experiments. Another approach, however, is to start from some ideas of the behavior of partons in the non-perturbative hadron, and build a model based on that behavior. The advantage with this approach is that the successes and failures of such a model allows us to get insight into the non-perturbative QCD dynamics. The model presented here, and described in detail in [1, 2], describes the F_2 structure function of the proton, as well as sea quark asymmetries of the nucleon. Most noteworthy, our model predicts an asymmetry between the momentum distributions of strange and anti-strange quarks in the nucleon of the same order as the newly reported results from NuTeV [3]. The model also suggests an intrinsic charm component in the proton.

This work extends the model previously presented in [4]. The model gives the four-momentum k of a single probed valence parton (see Fig. 1a for definitions of momenta) by assuming that, in the nucleon rest frame, the shape of the momentum distribution for a parton of type i and mass m_i can be taken as a Gaussian

$$f_i(k) = N(\sigma_i, m_i) \exp \left\{ - \left[(k_0 - m_i)^2 + k_x^2 + k_y^2 + k_z^2 \right] / 2\sigma_i^2 \right\} \quad (1)$$

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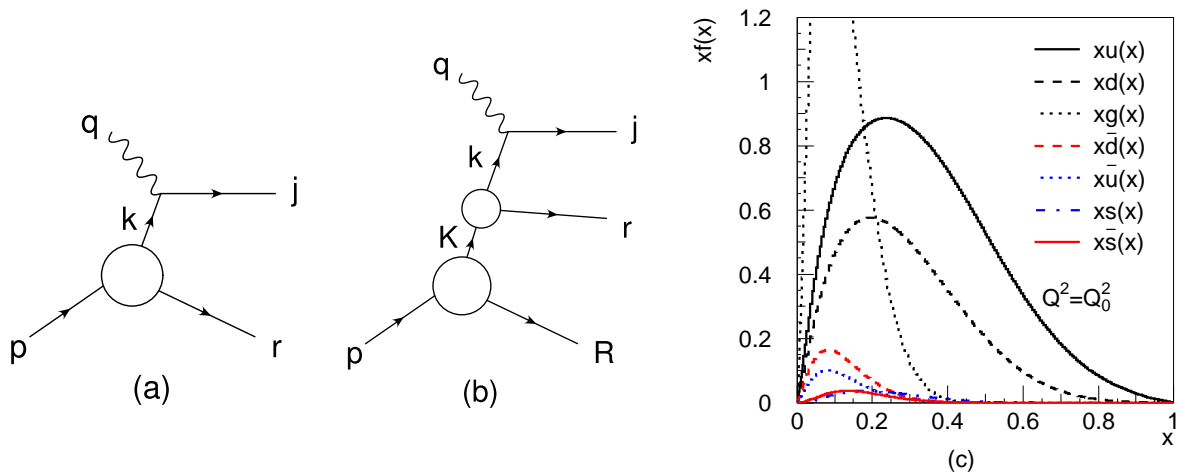


FIGURE 1. Illustration of the processes probing (a) a valence parton in the proton and (b) a sea parton in a hadronic fluctuation (letters are four-momenta). (c) shows the resulting parton distributions at the starting scale Q_0 .

which may be motivated as a result of the many interactions binding the parton in the nucleon. The width of the distribution should be of order hundred MeV from the Heisenberg uncertainty relation applied to the nucleon size, *i.e.* $\sigma_i = 1/d_N$. The momentum fraction x of the parton is then defined as the light-cone fraction $x = k_+/p_+$. We impose constraints on the final-state momenta in order to obtain a kinematically allowed final state, which also ensures that $0 < x < 1$ and $f_i(x) \rightarrow 0$ for $x \rightarrow 1$. Using a Monte Carlo method these parton distributions are integrated numerically without approximations.

To describe the dynamics of the sea partons, we note that the appropriate basis for the non-perturbative dynamics of the bound state nucleon should be hadronic. Therefore we consider hadronic fluctuations, for the proton

$$|p\rangle = \alpha_0 |p_0\rangle + \alpha_{p\pi^0} |p\pi^0\rangle + \alpha_{n\pi^+} |n\pi^+\rangle + \dots + \alpha_{\Lambda K} |\Lambda K^+\rangle + \dots \quad (2)$$

Probing a parton i in a hadron H of a baryon-meson fluctuation $|BM\rangle$ (see Fig. 1b) gives a sea parton with light-cone fraction $x = x_H x_i$ of the target proton. The momentum of the probed hadron is given by a similar Gaussian, but with a separate width parameter σ_H . Also here, kinematic constraints ensure that we get a physically allowed final state. The procedure gives $x_H \sim M_H/(M_B + M_M)$, *i.e.* the heavier baryon gets a harder spectrum than the lighter meson. The normalization of the sea distributions is given by the normalization coefficients α_{BM}^2 of Eq. (2). These cannot be calculated from first principles in QCD and are therefore taken as free parameters to be fitted using experimental data.

The resulting valence and sea parton x -distributions apply at a low scale Q_0^2 , and the distributions at higher Q^2 are obtained using perturbative QCD evolution at next-to-leading order.

The model has in total four shape parameters and three normalization parameters, plus the starting scale, to determine the parton densities $u, d, g, \bar{u}, \bar{d}, s, \bar{s}$. These are (with

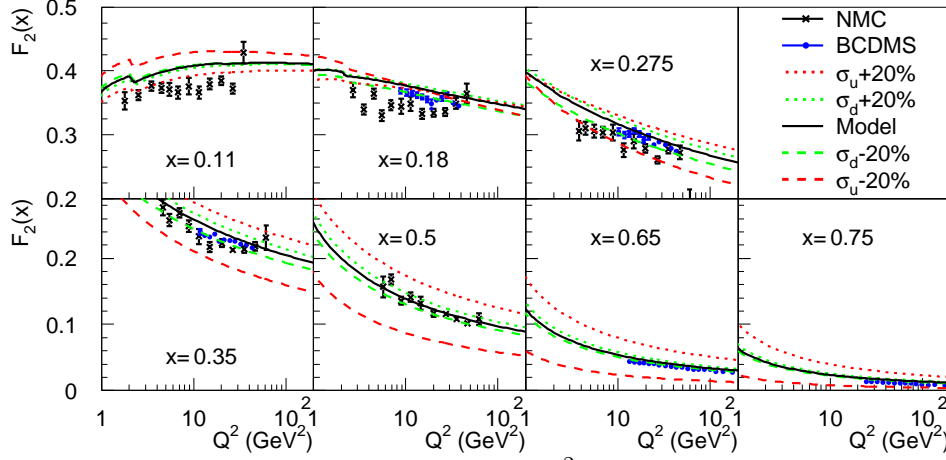


FIGURE 2. The proton structure function $F_2(x, Q^2)$ for large x values; NMC and BCDMS data [5, 6] compared to our model, also showing the results of $\pm 20\%$ variations of the width parameters σ_u and σ_d for the u and d valence distributions.

values resulting from fits to experimental data as described below):

$$\begin{aligned} \sigma_u &= 230 \text{ MeV} & \sigma_d &= 170 \text{ MeV} & \sigma_g &= 77 \text{ MeV} & \sigma_H &= 100 \text{ MeV} \\ \alpha_{p\pi^0}^2 &= 0.45 & \alpha_{n\pi^+}^2 &= 0.14 & \alpha_{\Lambda K}^2 &= 0.05 & Q_0 &= 0.75 \text{ GeV} \end{aligned} \quad (3)$$

The resulting parton densities are shown in Fig. 1(c).

In order to fix the values of the model parameters, we make a global fit using several experimental data sets: Fixed-target F_2 data to fix large- x (valence) distributions (Fig. 2); HERA F_2 data for the gluon distribution width and the starting scale Q_0 ; \bar{d}/\bar{u} -asymmetry data for the normalizations of the $|p\pi^0\rangle$ and $|n\pi^+\rangle$ fluctuations (see Fig. 4); and strange sea data to fix the normalization of fluctuations including strange quarks (see Fig. 5a). We have also compared with W^\pm charge asymmetry data as a cross-check on the ratio of Gaussian widths for the u and d valence quark distributions (Fig. 3). It is interesting to note that this simple model can describe such a wealth of different data with just one or two parameters per data set.

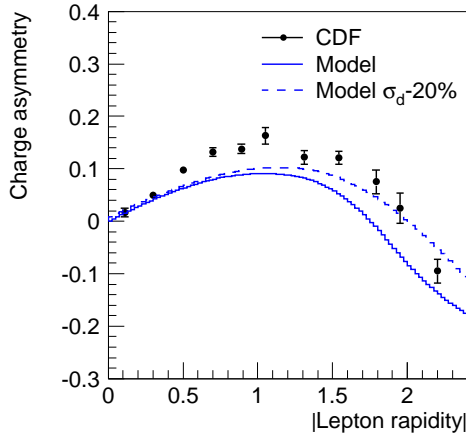


FIGURE 3. The charge asymmetry for leptons from W^\pm -decays in $p\bar{p}$ collisions at the Tevatron [7] compared to our model, with best-fit parameters and a 20% reduced width of the valence d quark distribution.

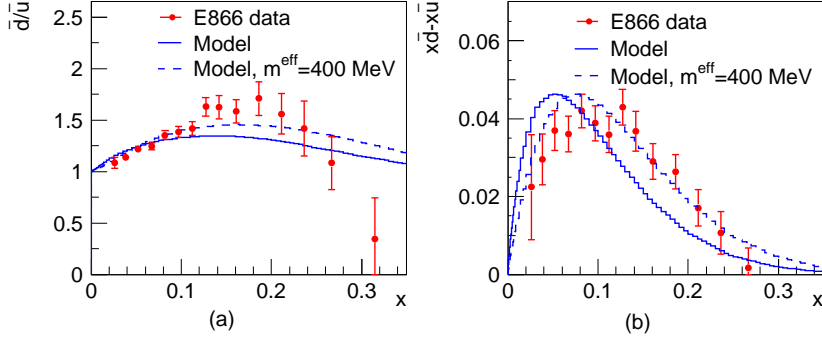


FIGURE 4. Comparison between our model and data from the E866/NuSea collaboration [8]: (a) $\bar{u}(x)/\bar{d}(x)$ (b) $xd(x) - xu(x)$. The full line uses the physical pion mass, while the dashed line uses an effective pions mass $m^{\text{eff}} = 400$ MeV as discussed in the text.

In our model, the shape difference between the valence u and d distributions in the proton, apparent from the W^\pm charge asymmetry data, is described as different Gaussian widths. This would correspond to a larger effective volume in the proton for d quarks than for u quarks, an effect which could conceivably be explained by Pauli blocking of the u quarks.

Since the proton can fluctuate to π^0 and π^+ by $|p\pi^0\rangle$ and $|n\pi^+\rangle$, but to π^- only by the heavier $|\Delta^{++}\pi^-\rangle$, we get an excess of \bar{d} over \bar{u} in the proton sea. Interestingly, the fit to data improves when we use a larger effective pion mass of 400 MeV (see Fig. 4). This might indicate that we have a surprisingly large coupling to heavier ρ mesons, or that one should use a more generic meson mass rather than the very light pion.

The lightest strange fluctuation is $|\Lambda K^+\rangle$. If we let this implicitly include also heavier strange meson-baryon fluctuations, we can fit the normalization $\alpha_{\Lambda K}^2$ to strange sea data (see Fig. 5a). The result corresponds to $\int_0^1 (xs + x\bar{s})dx / \int_0^1 (x\bar{u} + x\bar{d})dx \approx 0.5$, in agreement with standard parton density parameterizations. We note that this indicates a normalization $\propto 1/\Delta M_{BM} = 1/(M_B + M_M - M_p)$ rather than $\propto 1/\Delta M_{BM}^2$, as expected from old-fashioned perturbation theory. The fluctuation parameters are taken from the light sea results, $\sigma_H = 100$ MeV and $\sigma_q = \sigma_d^{\text{proton}} = 170$ MeV as discussed in [1].

Since the s quark is in the heavier baryon Λ and the \bar{s} quark is in the lighter meson K^+ ,

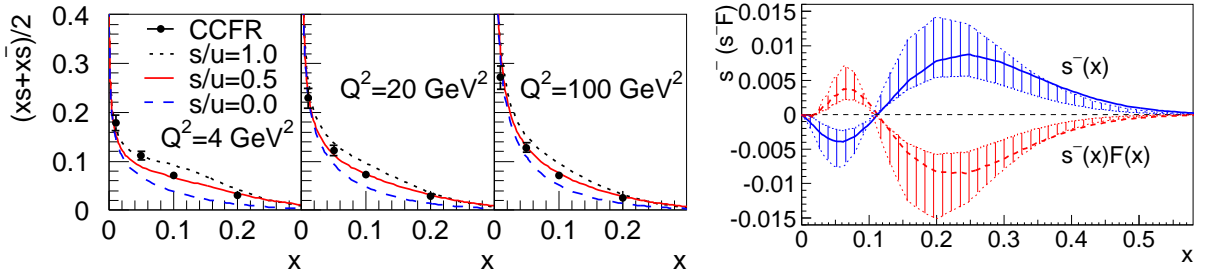


FIGURE 5. (a) CCFR data [9] on the strange sea distribution $(xs(x) + x\bar{s}(x))/2$ compared to our model based on $|\Lambda K\rangle$ fluctuations with different normalizations. (b) The strange sea asymmetry $s^-(x) = xs(x) - x\bar{s}(x)$ (at $Q^2 = 20$ GeV 2) from the model and combined with the function $F(x)$ accounting for NuTeV's analysis giving $\Delta \sin^2 \theta_W = \int_0^1 dx s^-(x)F(x) = -0.0017$. The uncertainty bands correspond to the uncertainties for S^- and $\Delta \sin^2 \theta_W$ quoted in the text.

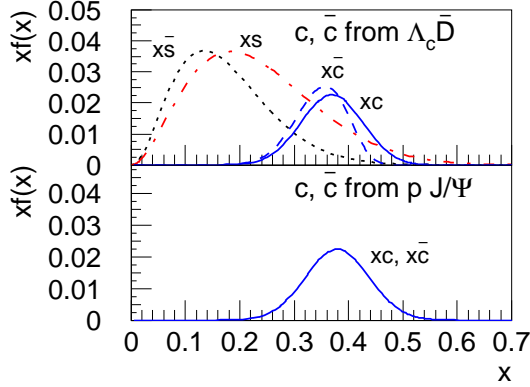


FIGURE 6. (a) Comparison between the strange and charm sea obtained from our model with the inclusion of the $\Lambda_C \bar{D}$ fluctuation. The normalization is here taken to be $\propto 1/(M_B + M_M - M_p)$ as suggested by strange sea data. (b) The charm quark distributions from the $p J/\psi$ fluctuation (the c and \bar{c} distributions are identical with this fluctuation). Note that the distributions are very similar to those from the $\Lambda_C \bar{D}$ distribution, except for the small asymmetry between c and \bar{c} .

we get a non-zero asymmetry $S^- = \int_0^1 dx [xs(x) - x\bar{s}(x)]$ in the momentum distribution of the strange sea, as seen in Fig. 5b and 6a. Depending on details of the model, we get the range $0.0010 \leq S^- \leq 0.0023$ for this asymmetry.

This is especially interesting in connection to the NuTeV anomaly [10]. NuTeV found, based on the observable $R^- = \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2 \theta_W$, a 3σ deviation of $\sin^2 \theta_W$ compared to the Standard Model fit: $\sin^2 \theta_W^{\text{NuTeV}} = 0.2277 \pm 0.0016$ compared to $\sin^2 \theta_W^{\text{SM}} = 0.2227 \pm 0.0004$. However, an asymmetric strange sea would change their result, since ν only have charged current interactions with s and $\bar{\nu}$ with \bar{s} . Using the folding function provided by NuTeV to account for their analysis, the s - \bar{s} asymmetry from our model gives a shift $-0.0024 \leq \Delta \sin^2 \theta_W = \int_0^1 dx s^-(x) F(x) \leq -0.00097$, *i.e.* the discrepancy with the Standard Model result is reduced to between 1.6σ and 2.4σ , leaving no strong hint of physics beyond the Standard Model.

In our model, it is also natural to consider fluctuations involving heavy quarks. Assuming that the hadronic fluctuation description is still valid for the proton fluctuating into charmed baryon-meson pairs, the lightest such fluctuations are $p \rightarrow \Lambda_C \bar{D}$ and $p \rightarrow p J/\psi$. Taking these fluctuations into account implies that there should be an intrinsic charm component in the proton at intermediate $x \sim 0.4$. This component is quite different from the purely perturbative charm component from gluon splitting, which falls steeply with x (see Fig. 7). The intrinsic charm component should be present from the scale where the momentum transfer can realize the charmed fluctuation.

The resulting distributions of c and \bar{c} at the starting scale are shown in Fig. 6. In Fig. 6a the distributions from the $|\Lambda_C \bar{D}\rangle$ fluctuation are shown compared with the s and \bar{s} distributions. The fluctuation parameters (σ_H and σ_q) are taken to be the same as for the light quark fluctuations, just as for the strange sea. However, the sensitivity of the result on the precise values of these parameters is small. The normalization is in Fig. 6 taken to be $\propto 1/\Delta M_{BM}$ (to be discussed below), in order to easily compare the shapes of the strange and charmed sea. In this case, there is an asymmetry between the c and \bar{c} distributions, similar to that of the strange sea, but much smaller due to the similarity in mass between the Λ_C (2285 MeV) and the \bar{D} (1865 MeV). Fig. 6b shows the distributions from the $|p J/\psi\rangle$ fluctuation. They are very similar to that of the $|\Lambda_C \bar{D}\rangle$ distributions, except that the asymmetry is missing since both the c and the \bar{c} are here in the meson. From Fig. 6 it is clear that an investigation of the intrinsic charm distributions from our

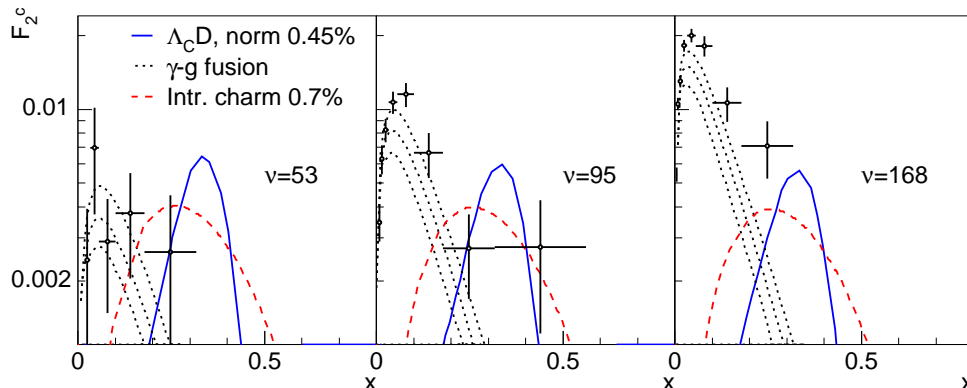


FIGURE 7. Data for the charm structure function F_2^c from the EMC experiment [12], compared to our model results with the best-fit normalization (solid curve). The dotted curves show the perturbative QCD prediction for $\gamma g \rightarrow c\bar{c}$ from [13], with three different choices for the renormalization and factorization scales. For comparison, the intrinsic charm distribution of [11] is also shown, with the 0.7% normalization allowed according to [13] (dashed curve).

model is not much affected by the precise nature of the dominating fluctuation mode, and in the following we will use only the $|\Lambda_c \bar{D}\rangle$ fluctuation. Note that the shape of our intrinsic charm component is somewhat different from that in the intrinsic charm model by Brodsky et al. [11], which is based on partonic fluctuations $p \rightarrow u u d c \bar{c}$ (see Fig. 7).

The normalization used in Fig. 6 corresponds to a relative importance between different mass states proportional to $1/\Delta M_{BM}$, as suggested by the strange sea fit to CCFR data. This normalization would give an intrinsic charm component ($(c + \bar{c})/2$ integrated number density) of 0.9%. However, it might be more appropriate to use a normalization $\propto 1/\Delta M_{BM}^2$ (as given by old-fashioned perturbation theory) compared to the strange fluctuations, corresponding to an intrinsic charm component of 0.18%.

The only experimental data for the large- x charmed structure function $F_2^c = \frac{4}{9}x(c + \bar{c})$ (at leading order) comes from the EMC experiment [12], which measured charmed hadron production in muon-proton scattering. There, an intriguing excess was found in the largest x bins, compared to the perturbative photon-gluon fusion expectation. A later analysis gave further evidence that the excess cannot easily be attributed to standard perturbative production channels [13]. Intrinsic charm was immediately suggested as an explanation for the excess, but the shape of the charm distribution in the original intrinsic charm model is not optimal to explain the EMC excess. In Fig. 7, the EMC data is shown in bins of $\nu = Q^2/2M_p x$, together with the result from our model, evolved in Q^2 using NLO QCD evolution [14]. Here we use the best-fit normalization, corresponding to 0.45% intrinsic charm. This lies between the two normalizations discussed above, which should not be surprising since the energy denominator only gives an order-of-magnitude estimate. For comparison, we also show the intrinsic charm distribution of [11] with the largest normalization allowed by the EMC data according to [13] (0.7% intrinsic charm), and the perturbative photon-gluon fusion results from [13].

As can be seen from Fig. 7, the shape of the intrinsic charm distribution in our model seems to fit the data very well, giving an enhancement at precisely the right values of x .

Unfortunately, the statistics of the EMC result is too small to allow any discrimination between different models for intrinsic charm, and measurements of the charm structure function at HERA (H1[15] and ZEUS[16]) are at too low values of x to contribute to our understanding of intrinsic charm. If a future experiment would measure the large- x charm structure function with large statistics, it would be very interesting to get a decisive verification of the presence of intrinsic charm in the proton.

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